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In-Situ Cosmogenic exposure ages from the Isle of Skye, North West Scotland- Implications for the timing of deglaciation and readvance from 15-11ka.

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Abstract

We present 10 *in-situ* cosmogenic exposure ages from two moraines on the Isle of Skye. The Strollamus medial moraine was deposited during deglaciation of the Devensian ice sheet and yields a mean exposure age from five samples of 14.3±0.9 ka. The moraine age indicates that a significant ice mass existed on Skye at the time of a regional readvance recorded in Wester Ross, NW Scotland. Taken at face value the ages suggest that deglaciation did not occur until well into Greenland Interstade 1. The Slapin moraine represents the local limit of the Loch Lomond Readvance (LLR) and yields a mean exposure age from five samples of 11.5±0.7 ka which is consistent with deposition relating to the LLR. These ages suggest that the maximum extent may have been reached late in the stadial and that some glaciers may have remained active until after the climatic amelioration that marks its end. This scenario is considered unlikely given the nature of climate during this period which leads us to call for a locally calibrated production rate.

Keywords: Cosmogenic exposure ages, Wester Ross Readvance, Loch Lomond Readvance, Scotland, moraines.

Introduction

The former British Ice Sheet (BIS) existed in a climatically sensitive region of the North Atlantic and as a result it is believed that its margin responded to short lived climatic variations that punctuated the last deglacial cycle (McCabe and Clark, 1998; Knutz *et al*., 2001; Scourse *et al.,* 2009; Hibbert *et al*., 2010). In order to fully investigate links between the ice sheet's dynamics and short-lived climate change it is vital to build a chronology of ice margin retreat and fluctuation. Many studies have focussed on delimiting the former extent and deglaciation pattern of ice in Scotland (Charlesworth, 1956; Sissons *et al*., 1973; Ballantyne, 1989; Bradwell *et al*., 2008a). While much of the initial chronology was based on pollen data and radiocarbon dates (Rose *et al*., 1988; Walker *et al*., 1988) recently, new techniques such as cosmogenic surface exposure dating (SED) have been utilised to further constrain the ice sheet's chronology (Stone and Ballantyne, 2006; Golledge *et al*., 2007; Bradwell *et al*., 2008b; Ballantyne *et al*., 2009).

The result of this previous work was the emergence of consensus regarding the behaviour of the last BIS during deglaciation following the Last Glacial Maximum (LGM), 26-21 ka. It is now accepted that the BIS reached the shelf edge at the LGM (Stoker *et al*., 1993; Austin and Kroon, 1996) and covered all of Scotland (Ballantyne, 2010). Deglaciation is believed to have commenced sometime before the climatic amelioration that marks the end of Greenland Stadial 2 (GS-2; 23.3-14.7ka before 2000 ce (b2k); Lowe *et al*., 2008), with deglaciation of the continental shelf west of the Hebrides by c.15 ka, at which time ice was located at, or near, the present coastline (Austin and Kroon, 1996; Bradwell *et al.,* 2008a). Further deglaciation was interrupted by local and regional readvances (Robinson and Ballantyne, 1979; Benn, 1997) but it was generally presumed that Scotland became effectively ice free during GI-1 (14.7-12.9ka b2k) (Sissons, 1967; Bowen *et al*., 1986).

Recent work using SED has led to this ice-free paradigm being challenged. A major regional readvance in NW Scotland, termed the Wester Ross Readvance (WRR) was initially dated to 16.3 ka and tentatively correlated to Heinrich Event 1 (Everest *et al*., 2006). However new SED dates from several moraines associated with this readvance place their deposition within the early part of GI-1 and suggest the persistence of ice across low ground in NW Scotland (Bradwell *et al.,* 2008b; Ballantyne *et al*., 2009). These results introduce the possibility that Scotland did not become ice free during GI-1 as previously presumed.

The marked deterioration in climate observed at the start of GS-1 (12.9-11.7ka b2k) in the Greenland ice cores (Dansgaard *et al*., 1989; Steffensen *et al*., 2008) is also recorded in the palaeo-climate of Scotland (Brooks and Birks, 2000). The cooling resulted in a period of glacier expansion termed locally the 'Loch Lomond Readvance' (LLR). A major ice cap grew in Western Scotland, with satellite ice fields on some islands including Mull and Skye, as well as in the NW Highlands and the Grampians. Golledge (2010) provides a good review of this period of glaciation and some of the debates surrounding its extent and timing. Initial radiocarbon dates suggested that glaciers in the Western Highlands reached their maximum extent early in GS-1 (Sissons, 1967; Lowe, 1978; Sutherland, 1981). This view is supported by modelling work that suggests the ice cap could have reached its maximum extent in only 550 years (Hubbard, 1999). However, recent work provides evidence that at least some outlet glaciers of the main ice cap reached their maximum extent towards the end of GS-1 (Fabel *et al*., 2010; MacLeod *et al*., 2010; Palmer *et al*., 2010). This may be the result of internal glacial dynamics causing individual glaciers to reach their maximum extents diachronously or alternatively, it may be a climatically driven effect with wider implications for glacier modelling of this time.

Regional Context

The Isle of Skye (Figure 1) is the largest of the Hebridean islands and contains some of the most spectacular glaciated mountain scenery in Scotland. Offshore sedimentary evidence suggests that Skye was glaciated several times during the Quaternary (Bowen *et al*., 1988; Scourse *et al*., 2009; Hibbert *et al*., 2010). However, direct onshore evidence only exists for the last two episodes; the Late Devensian and the LLR as these have overprinted or erased any evidence of previous glaciations.

Evidence for LGM ice extent and deglaciation.

During the LGM the Cuillin mountains of Skye nourished an ice dome (Skye Ice Dome [SID]) which deflected ice moving west from the mainland (Harker, 1901; Ballantyne *et al*., 1991). This view is supported by evidence from glacial striae and erratics. On the island of Soay occurrences of mainland erratics suggest that ice from the mainland reached close to the south coast of Skye (Ballantyne *et al.,* 1991). These erratics may mark the confluence of the SID and mainland ice at some point during the LGM. The absence of mainland erratics on the southern coast of Skye is evidence that this area was not a depositional site for mainland ice. However, glacial striae on the southern slopes of the Black Cuillin suggest westerly flow of ice (Ballantyne *et* *al.,* 1991). Thus either SID ice was strongly deflected or at some point during the LGM mainland ice did flow across this part of Skye.

To the north and east of the Cuillins it has been inferred from the distribution of erratics that the confluence of the SID and mainland ice followed the narrow straight that separates Skye from Scalpay and Raasay (Harker, 1901). Mainland erratics occur at all altitudes (0 to ~400 m) on these islands, suggesting that they were completely over-run by mainland ice during the LGM. In contrast, in central Skye mainland erratics only occur below the marine limit and have been interpreted as being ice rafted (Ballantyne *et al.,* 1991).

Overall, the SID at the LGM had an asymmetric configuration. Its extent was constrained in the northeast, east and south by mainland ice flow. To the west and northwest locally nourished ice extended across much of Skye. The ice attained a minimum thickness of 800 m over the central part of the SID (Dahl *et al*., 1996). As offshore evidence indicates the BIS reached the shelf edge it is possible that the ice was considerably thicker, although efficient ice evacuation by palaeo-ice streams could have limited the ice thickness. The majority of ice sourced on Skye flowed north and fed the Minch palaeo-ice stream which is inferred from the presence of large scale streamlined glacial landforms. The Minch palaeo-ice stream drained a large section of the northwest sector of the BIS at the LGM and had an important influence on ice sheet dynamics and configuration (Stoker and Bradwell, 2005; Bradwell *et al*., 2007).

There is little documented evidence relating to the pattern of ice sheet deglaciation on Skye immediately following the LGM. In the Red Cuillin above Strollamus a bouldery moraine extends SSE-NNW over a distance of several kilometers (Figure 2). The moraine is composed of locally sourced granitic and gabbro boulders. It was initially interpreted as a lateral moraine pre-dating the LLR (Ballantyne, 1988) but has since been re-interpreted as a medial moraine marking the confluence of the SID and mainland ice (Benn, 1990). The Strollamus moraine is one of only two ice sheet moraines documented in the literature, the other being a small collection of arcuate ridges in the Kyleakin Hills (Ballantyne, 1988). There is evidence on Skye for at least one readvance or stillstand that predates the LLR as the evidence for it occurs outwith the LLR ice limtis (Benn, 1997). It is unknown whether the various lines of evidence reported by Benn (1997) represent a single readvance or a series of fluctuations of the SID margin during deglaciation. The timing of this readvance(s) and whether it is contemporaneous with the WRR reported elsewhere in northwest Scotland has, so far, not been established (Bradwell *et al.,* 2008b; Ballantyne *et al.,* 2009).

Evidence for the LLR ice extent and deglaciation.

The features related to the LLR on Skye are of exceptional clarity. Much work involved delimiting the LLR and their now exists a good understanding of the glacial limits associated with this readvance (Sissons, 1977; Walker *et al.*, 1988; Ballantyne, 1989).

During the LLR the central Cuillin Hills nourished a large ice field with an area of ~155 km^2 (Figure 3). In addition seven individual corrie glaciers grew in the west facing corries of the Cuillins (Ballantyne, 1989). The Cuillin ice field fed outlet glaciers, the largest of which flowed north down Glen Sligachan and fed the Drynoch, Varigill and Sligachan glaciers (Ballantyne, 1989; Ballantyne *et al.,* 1991). Satellite corrie glaciers existed in the eastern Red Hills, Kyleakin Hills, Trotternish and on MacLeod's Tables in Duirnish (Ballantyne, 1990; Ballantyne and Benn, 1994).

Abundant moraine segments and features related to deglaciation of LLR ice are observable on Skye. Their study has led to the proposal that LLR glaciers on Skye experienced a two-phase retreat (Benn *et al.*, 1992). Initial retreat was characterised by active ice retreat with minor oscillations of the ice margin resulting in sequences of recessional moraines. The second phase of retreat was largely uninterrupted and accompanied by local ice stagnation with no associated recessional moraines. It has been proposed that the first stage of retreat was initiated by a change in precipitation prior to the climatic amelioration that marked the end of GS-1 and that the second phase was in response to the sustained temperature increase associated with this amelioration (Benn *et al.,* 1992). This style of retreat is different to that reported from northwest Scotland of active retreat throughout deglaciation (Bennett and Boulton, 1993) and may have been a function of sediment availability.

<u>Age control.</u>

Previous attempts at absolute dating of features on Skye relating to the time period following the LGM are limited. Stone *et al.*,(1998) obtained two ^{36}Cl exposure ages from ice scoured bedrock on a col in Trotternish that gave ages of 16.4±1.2 ka and 16.7±1.3 ka. The significance of these dates is discussed in a later section.

Several radiocarbon ages have been published from various sites around the island. They have produced varying results and highlighted some inherent issues. The majority of theses radiocarbon dates were obtained some decades ago and are derived from bulk organic samples (Williams, 1977; Walther, 1984; Walker *et al.*, 1988). Walker and Lowe (1990) highlight the issue of contamination with older carbon being incorporated into the samples providing a significant bias. This bias leads to erroneously old ages and in some cases the error approaches 1 ka. It is thus considered that these ages are not reliable for constraining the timing of the last deglaciation on Skye (Walker and Lowe, 1990).

Aims and Objectives.

This paper aims to provide constraints on the persistence of ice on Skye during deglaciation by dating the Strollamus medial moraine. With the suggestion of ice cover over low ground during GI-1 in Northwest Scotland (Bradwell *et al.,* 2008b) it is important to establish if ice was present in other areas in order to fully understand the response of the BIS to rapid climate change. The recent suggestion of a late LLR maximum for some outlet glaciers of the main Scottish ice cap (eg: MacLeod *et al.,* 2010) is examined with respects to a smaller ice mass which may be expected to be more sensitive to climatic fluctuations. The ages presented here are the first SED from moraines on Skye. As such they provide important data for further constraining the timing of events during the deglacial period, 15-11 ka.

Methods

In situ terrestrial cosmogenic nuclides are produced near the surface of the Earth by interactions of minerals with secondary cosmic radiation (Gosse and Phillips, 2001; Dunai, 2010). In order to determine exposure ages it is necessary to measure the concentration of cosmogenic nuclides within a rock surface and to use an average nuclide production rate for the period of exposure to calculate the age. This production rate varies temporally and spatially due to variability in the Earth's magnetic field strength with time and location (Masarik *et al*., 2001). The production rate is also dependent on the depth of atmosphere through which the secondary cosmic radiation passes through, i.e.: the site altitude (Gosse & Philips, 2001). Balco *et al*. (2008) compiled the available calibration data for production rates in order to standardise the results of researchers presenting exposure ages obtained from cosmogenic nuclides.

Ten samples were collected for cosmogenic ^{10}Be analysis. Five samples were collected from the Strollamus moraine (Figure 2) along a transect of ~100 m on the top of moraine. Five samples were collected along a ~50 m transect on top of a mapped LLR moraine limit on the eastern shore of Loch Slapin (Figure 4). Both moraines contain subrounded and facetted boulders which are considered indicative of subglacial transport (Ballantyne *et al*., 2009). Sample locations and characteristics are shown in Table 1. All samples were taken from the top surface of granitic boulders using hammer and chisel. We sampled the largest boulders available and assessed them to minimise the possibility that they had undergone post-depositional movements. Due to the absence of overlooking cliffs in the vicinity of our sample locations it is considered unlikely that any of our boulders were deposited paraglacially.

Sample locations were recorded using hand-held GPS and altitudes confirmed from OS 1:25000 topographic maps. For each sample the topographic shielding was measured as outlined on the CRONUS-Earth website (http://hess.ess.washington.edu/math; Balco *et al*., 2008). No correction for isostatic rebound is made as the temporal variability of change is not well constrained (Golledge *et al*., 2007) and in any event the effect of this would not be significant or alter our conclusions. Sample thickness was measured and the samples were crushed to <710 μm grain size at the University of St Andrews. Separation and purification of quartz was carried out at the University of Glasgow.

Beryllium extraction was carried out at the University of Glasgow Cosmogenic Isotope Laboratory at the Scottish Universities Environmental Research Centre (SUERC). Methods followed are modified from Child *et al*. (2000). Beryllium isotope ratios of 10 samples and two procedural blanks were measured at the SUERC Accelerator Mass Spectrometry (Williams) Laboratory.

The ages were calculated using the CRONUS-Earth exposure age calculator v2.2 (http://hess.ess.washington.edu/math; Balco *et al*., 2008). In table 2 we present the ages obtained using the 'Lm' scaling scheme of Balco *et al*. (2008), which provide the closest fit to existing calibration data, and the 'Du' scaling scheme which yields the oldest ages for all samples. Of the other schemes, the 'Li' scheme yields ages slightly younger than the 'Lm' scheme, and the 'De' scheme gives ages almost identical to the 'Du' scheme. Ages quoted in the text are those calculated using the Lm scaling scheme, no correction for snow coverage and an erosion rate of 1 $mm.ka^{-1}$ as erosion rates of glaciated crystalline rocks rarely exceed 1 $mm.ka^{-1}$ (André, 2002). The effects of various scaling schemes and differing erosion rates is discussed by Ballantyne (2010) but is not a significant factor and would not alter any of our conclusions.

Results

The samples from the Strollamus moraine range from 14.9±1.6 ka to 13.5±1.4 ka and yield a weighted mean exposure age of 14.3±0.9 ka. The analytical error associated with the ^{10}Be surface exposure age of sample STR 05-08 is large. This is because this sample had a very low quartz yield (3 g of pure quartz). As a result the number of events recorded during the AMS analysis was low and the associated error high. Despite this, the age is in agreement with the other samples, which allows us to have confidence in the result.

The mean exposure age of 14.3±0.9 ka falls within the bounds of GI-1 (Figure 5). This age is consistent with ^{10}Be ages of 12.9±1.3 - 14.1±1.4 ka and 12.9±1.2 - 15.2±1.8 ka obtained from a suite of moraines associated with the WRR further north (Bradwell *et al.,* 2008b; Ballantyne *et al.,* 2009).

The samples from Loch Slapin range from 12.3±1.2 ka to 10.7±1.1 ka. The samples yield an weighted mean exposure age of 11.5±0.7 ka. This age falls outside of GS-1 (12.9-11.7ka b2k) as defined by the INTIMATE group (Lowe *et al*., 2008). Of the 5 ages, only sample SLAP-1 falls within GS-1 (Figure 5).

Both moraines are considered to have stabilised quickly and thus the ages represent the time of moraine deposition. The Strollamus moraine contains boulders that rest on ice moulded bedrock and is deposited across a slope with an average gradient of ~10%. Given both these facts it is considered unlikely that there was any lag at between the deposition of the moraine and the commencement of cosmogenic nuclide accumulation. The Slapin moraine retains a steep profile with a well defined crest, compared to a diffuse profile indicative of significant post-depositional adjustment. In addition the exceptionally wet climate would lead to vegetation being established quickly, stabilising the moraine and currently peat formation is causing the moraine to accrete rather than degrade. These factors lead us to conclude that post depositional shielding is unlikely to be a significant bias in our results.

Each set of samples from the two moraines overlap at 1σ uncertainty and are thus in agreement. Tested on the basis of internal (analytical) uncertainties, the dating results from the Strollamus and Slapin moraines are significantly different (p value < 0.01) demonstrating that it is possible to differentiate between the LLR and WRR within the resolution of SED.

Discussion

The Strollamus moraine has been interpreted as a medial moraine that marks the confluence of locally nourished ice and ice sourced from the mainland. The evidence for this interpretation is outlined by Benn (1990). He argues firstly, that the absence of an equivalent moraine on Scalpay is evidence that it is not an ice marginal feature and secondly, that the lack of westward spill of the boulder train at the col below Am Meall is a result of ice being present at the col.

The granitic boulders that make up the Strollamus moraine were sourced from the shoulder of Beinn na Callich which lies c.2.5km to the south east of our sample site. Although the source would have been completely covered by ice during the LGM, during deglaciation Beinn na Callich would have become a nunatak while ice still covered the sample site. Therefore it is possible that, despite sampling subrounded and facetted boulders indicative of subglacial transport the boulders were transported supraglacially to the sample site. However, given the short transport distance from the source any exposure experienced by boulders transported supraglacially would not make a significant contribution to the total nuclide concentration.

As a medial moraine the Strollamus moraine does not provide conclusive evidence for a readvance as it would have been deposited as ice thinned. It does however, indicates that at the time of the WRR, ice was present on the east coast of Skye.

Two ^{36}Cl ages from the Storr to the North of our sample site yielded deglaciation ages of 16.4±1.2 ka and 16.7±1.3 ka (Stone *et al.,* 1998; Ballantyne, pers. Comm..) The implication of the Strollamus moraine being deposited during deglaciation is that the ice front only retreated ~30 km in ~3 ka. This retreat rate is less than the inferred rate of retreat from the shelf edge of 32±14 $km.ka^{-1}$ - 53±38 $km.ka^{-1}$ by a third to a fifth (Stone & Ballantyne, 2006). Such an inferred slowing of the retreat rate could be explained by a readvance prior to the thinning of ice and deposition of the Strollamus moraine. This possible readvance may be the equivalent to the WRR or it may pre-date it. This interpretation suggests that ice existed within the Inner Sound between Scalpay, Skye and the mainland at the time of the WRR. This would have represented a significant calving front and other calving margins have been extrapolated from the onshore moraines to the north (Ballantyne *et al.,* 2009). This introduces the possibility that the WRR may be recorded in some marine IRD records which could provide an independent means of correlating the WRR with a local and/or regional climate signal.

Bradwell *et al*. (2008b) and Ballantyne *et al*. (2009) proposed climatic forcing as the driver of the WRR. They argue that the short-lived deterioration in climate that marks GI-1d (14.1-13.9 b2k) initiated the glacier readvance responsible for the WRR moraines. Ballantyne *et al*. (2009) point out that uncertainties related to choices of scaling factors mean that glacier response to earlier or later climatic fluctuations (i.e.: GI-1b) cannot be ruled out. Our results do not allude further to this question.

Interpreting the Strollamus moraine as a GI-1 feature conflicts with radiocarbon ages obtained from a Lateglacial pollen site, Loch Ashik, 5 km to the east. By inference an ice mass depositing the Strollamus moraine (~150 m) would have covered Loch Ashik at an elevation of ~40 m. In Loch Ashik a basal radiocarbon date of 16.9±0.4 cal ka BP is reported, additional radiocarbon dates in the sequence span the period up until 13.1±0.2 cal ka BP (Walker *et al.,* 1988; calibrated using INTCAL09). This coincides with the period when ice is interpreted to be in existence 5km to the west. Walker *et al*. (1988) acknowledge the fact that the radiocarbon ages from this site are consistently “too old”. They ascribe this to the in-washing of older carbon. The issue of erroneously old radiocarbon ages has also been highlighted at other Late Glacial sites (Bradwell *et al.,* 2008b). The reliability of results based on bulk sediment samples is questionable as they frequently contain older detrital material and can be subject to a mineral carbon error (Lowe, 1991; Walker *et al*., 2001). The basal date from Loch Ashik is the same as the dates of deglaciation from the Storr (Ballantyne *et al.,* 1998), this would imply near instant deglaciation over a distance of ~40 km which is not consistent with the rates outlined previously. The ages outlined in this study further highlight the problem of potentially contaminated radiocarbon ages in Late Glacial sequences in Scotland and their use in constructing deglacial chronologies.

Within the sequence recorded at Loch Ashik are a number of tephra layers (Pyne-O'Donnell, 2007; Pyne-O'Donnell *et al*., 2008). One layer, the Penifiler tephra has a mid GI-1 stratigraphic position although it lacks independent age control. The earlier Borrobol tephra which occurs at 14.4 ka (Turney *et al*., 2006) is not reported within the Loch Ashik sequence although it may occur in a hitherto unsampled part of the basin. It is clear that at the time of deposition of the Penifiler tephra Loch Ashik could not have been ice covered. The occurrence of the Penifiler tephra provides an opportunity to constrain the timing of deposition of the Strollamus moraine if it can be independently dated.

The Slapin moraine (Figure 4) is mapped as the limit of the LLR in this locality (Ballantyne, 1989). For the same reasons outlined for the Strollamus moraine, any supraglacial transport of the boulders would not affect our conclusions. The mean exposure age of 11.5±0.7 ka would suggest that the LLR limit was reached after the termination of GS-1. Other results suggest that limits were achieved late in the stadial (Fabel *et al.,* 2010; MacLeod *et al.,* 2010; Palmer e*t al.,* 2010) while numerical modelling also simulates some outlet glaciers reaching a late maximum (Golledge *et al*., 2008). There are a limited number of cosmogenic dates relating to LLR moraines in the literature. Ballantyne *et al*. (2007) obtained ^{10}Be ages with a range of 10.4±1.8 ka – 12.4±1.6 ka from two former small corrie glaciers on Orkney while Golledge *et al*. (2007) obtained five ^{10}Be ages indicating ice cover over high ground in the Central Highlands ranging from 11.8±1.3 ka - 13.1±1.3 ka. These ages have been recalculated using the CRONUS-earth calculator for an erosion rate of 1mm.ka^{-1} to maintain a consistency with the ages presented here. Given the different geomorphic and glaciological setting of our sample site a direct comparison between these ages and the ones presented here is difficult. However, none of the ages appear irreconcilable with those obtained in this study.

SED using ^{10}Be on moraines relating to the LLR equivalent in the Alps suggest that glaciers remained active up until 11.2±1.0 ka (Ivy-Ochs *et al.*, 2009), an age that is consistent with the mean age of our samples. That glaciers experienced active retreat has been documented already on Skye, however deglaciation is inferred to have been initiated during GS-1 (Benn *et al.,* 1992). The presence of numerous recessional moraines within the Slapin limit show that active retreat occurred after the glacier retreated from this position. Our ages indicate that this active retreat occurred after the warming that marks the end of GS-1.

Brooks and Birks (2000) show that the GS-1 thermal minimum in Scotland occurred in the first half of the stadial. It is intuitive that this is when local glaciers were most likely to be at or near their maximum extent. Following this minimum the climate oscillated before the dramatic warming that marks the end of GS-1. It is during this time that the active retreat outlined by Benn *et al*. (1992) is thought to occur. Ballantyne (2007) reports that a summer warming in the order of 1° C would result in near total shrinkage of LLR glaciers on the Outer Hebrides. The warming during the second half of GS-1 was in the region of 1-1.5° C (Brooks and Birks, 2000). If glaciers on Skye were as sensitive to summer temperature as those on the Outer Hebrides it seems unlikely that they could survive such a temperature rise and still be near their maximum extent as is suggested by our ages. The ages reported here were calculated using the CRONUS calculator to allow comparison with other SED ages from different regions. However, this means they are calculated using a reference production rate derived from a global calibration data set with an uncertainty of 9% (Balco *et al.,* 2008) preventing resolution of events that occurred within a 1000 year timeframe. This problem could be overcome with the development of a precise local ^{10}Be production rate. Such a production rate, when combined with an ultra-pure beryllium carrier can obtain ^{10}Be dates with external uncertainties < 5% (Kaplan *et al*., 2010) which would be sufficient to resolve some of the questions highlighted by this and other SED studies in Scotland.

The suggestion of a late GS-1 glacial maximum now comes from a variety of localities and from work done using a variety of techniques including varve chronology (MacLeod *et al*., 2010; Palmer *et al*., 2010), SED (Fabel *et al*., 2010) and numerical modelling (Golledge *et al*., 2008). On the other hand there is a wide body of work supporting a maximum earlier in the stadial (Benn *et al.,* 1992; Brooks and Birks 2000; Hubbard 1999). SED can go someway to resolving this debate as it allows direct dating of evidence of glacial maximum, however resolving events within a c.1 ka timeframe is probably at the current limit of resolution of the technique and would require the development of a locally calibrated production rate.

Conclusions

The ^{10}Be exposure ages presented here represent the first moraines to be dated using SED on Skye. The excellent agreement shown by these dates allows us to have confidence in their accuracy and to draw the following conclusions.

The Strollamus moraine was deposited around the same time as the WRR recorded to the NW in mainland Scotland. Ice must have therefore existed over a significant amount of low ground in NW Scotland at this time. The SED results from this study and others (Ballantyne *et al.,* 2009; Bradwell *et al.,* 2008b) suggest that a significant ice mass existed during GI-1 and that it was possible that ice persisted across low ground until the climatic deterioration that marks the beginning of GS-1. This would have significant implications for glacial models of this time. This interpretation is in conflict with radiocarbon dates from a Late glacial pollen site

(Loch Ashik) and other sites show consistent disagreement with SED (Bradwell e*t al*., 2008b).

The results from the Loch Slapin moraine are consistent with it being a LLR feature and suggest that the glacier reached its maximum extent late in GS-1. This interpretation requires glaciers to survive a warming that has elsewhere been calculated to have been sufficient to result in near total disappearance of ice.

Resolving these issues requires the calculation of a locally calibrated ^{10}Be production rate which would allow workers to obtain exposure dates with uncertainties approaching 5%. This level of precision would be sufficient to resolve some of the questions highlighted by this study.

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Figure Captions

Figure 1. Location map of Skye showing the main locations mentioned in the text. The red dots are the locations of the two sample sites in this study. The numbered boxes 2, 3 and 4 correspond to the areas of Figures 2, 3 and 4 respectively.

Figure 2. Strollamus moraine and location of SED samples. The cross cutting relationship with the LLR ice limits can be clearly seen. Contours are at 100m intervals. Coordinates are BNG. Adapted from Benn *et al.,* (1992) and Ballantyne (1989).

Figure 3. Limit of the Loch Lomond Readvance in central Skye. Limits from Ballantyne (1989).

Figure 4. Loch Slapin area and location of SED samples. Coordinates are BNG. Adapted from Benn *et al.,* (1992).

Figure 5. Individual and cumulative probability curves for the exposure ages from the Strollamus and Slapin moraines using the Lm scaling scheme and 1mm yr^{-1} erosion rate plotted against NGRIP $\delta^{18}O$ curve (Rasmussen *et al.,* 2006). The mean value and full uncertainty for each moraine is also shown.